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INVENTOR(S)					
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<i>Additional inventors are being named on the _____ separately numbered sheets attached hereto</i>					
TITLE OF THE INVENTION (500 characters max)					
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ENCLOSED APPLICATION PARTS (check all that apply)					
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[Page 1 of 2]

Respectfully submitted,

SIGNATURE

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802-655-7222

Date

March 2, 2004

REGISTRATION NO.

41,791

(if appropriate)

Docket Number:

022B-03P**USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT**

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Effective 10/01/2003. Patent fees are subject to annual revision.

☒ Applicant claims small entity status. See 37 CFR 1.27TOTAL AMOUNT OF PAYMENT (\$)**80-****Complete if Known**

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First Named Inventor	ZAVRIYEV, Anton
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Attorney Docket No.	022B-03P

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Large Entity Fee Code (\$)	Small Entity Fee Code (\$)	Fee Description	Fee Paid
1001 770	2001 385	Utility filing fee	
1002 340	2002 170	Design filing fee	
1003 530	2003 265	Plant filing fee	
1004 770	2004 385	Reissue filing fee	
1005 160	2005 80	Provisional filing fee	80

SUBTOTAL (1) (\$)**80-****2. EXTRA CLAIM FEES FOR UTILITY AND REISSUE**

Total Claims	Extra Claims	Fee from below	Fee Paid
Independent	-20** =	X	
Multiple Dependent	-3** =	X	

Large Entity Fee Code (\$)	Small Entity Fee Code (\$)	Fee Description
1202 18	2202 9	Claims in excess of 20
1201 86	2201 43	Independent claims in excess of 3
1203 290	2203 145	Multiple dependent claim, if not paid
1204 86	2204 43	** Reissue independent claims over original patent
1205 18	2205 9	** Reissue claims in excess of 20 and over original patent

SUBTOTAL (2) (\$)**N/A**

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FEE CALCULATION (continued)**3. ADDITIONAL FEES**

Large Entity Small Entity

Fee Code (\$)	Fee Code (\$)	Fee Description	Fee Paid
1051 130	2051 65	Surcharge - late filing fee or oath	
1052 50	2052 25	Surcharge - late provisional filing fee or cover sheet	
1053 130	1053 130	Non-English specification	
1812 2,520	1812 2,520	For filing a request for <i>ex parte</i> reexamination	
1804 920*	1804 920*	Requesting publication of SIR prior to Examiner action	
1805 1,840*	1805 1,840*	Requesting publication of SIR after Examiner action	
1251 110	2251 55	Extension for reply within first month	
1252 420	2252 210	Extension for reply within second month	
1253 950	2253 475	Extension for reply within third month	
1254 1,480	2254 740	Extension for reply within fourth month	
1255 2,010	2255 1,005	Extension for reply within fifth month	
1401 330	2401 165	Notice of Appeal	
1402 330	2402 165	Filing a brief in support of an appeal	
1403 290	2403 145	Request for oral hearing	
1451 1,510	1451 1,510	Petition to institute a public use proceeding	
1452 110	2452 55	Petition to revive - unavoidable	
1453 1,330	2453 665	Petition to revive - unintentional	
1501 1,330	2501 665	Utility issue fee (or reissue)	
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1809 770	2809 385	Filing a submission after final rejection (37 CFR 1.129(a))	
1810 770	2810 385	For each additional invention to be examined (37 CFR 1.129(b))	
1801 770	2801 385	Request for Continued Examination (RCE)	
1802 900	1802 900	Request for expedited examination of a design application	

Other fee (specify)

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SUBTOTAL (3) (\$)**0****SUBMITTED BY**

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MODULATOR AUTOCALIBRATION METHODS FOR QKD

Field of the Invention

The present invention relates to quantum cryptography, and in particular relates to methods for automatically calibrating modulators in a two-way quantum key exchange (QKD) system.

Background of the Invention

Quantum key distribution involves establishing a key between a sender ("Alice") and a receiver ("Bob") by using weak (e.g., 0.1 photon on average) optical signals transmitted over a "quantum channel." The security of the key distribution is based on the quantum mechanical principal that any measurement of a quantum system in unknown state will modify its state. As a consequence, an eavesdropper ("Eve") that attempts to intercept or otherwise measure the quantum signal will introduce errors into the transmitted signals, thereby revealing her presence.

The general principles of quantum cryptography were first set forth by Bennett and Brassard in their article "Quantum Cryptography: Public key distribution and coin tossing," Proceedings of the International Conference on Computers, Systems and Signal Processing, Bangalore, India, 1984, pp. 175-179 (IEEE, New York, 1984). Specific QKD systems are described in publications by C.H. Bennett et al entitled "Experimental Quantum Cryptography" and by C.H. Bennett entitled "Quantum Cryptography Using Any Two Non-Orthogonal States", Phys. Rev. Lett. 68 2121 (1992).

The general process for performing QKD is described in the book by Bouwmeester et al., "The Physics of Quantum Information," Springer-Verlag 2001, in Section 2.3, pages 27-33. During the QKD process, Alice uses a random number generator (RNG) to generate a random bit for the basis ("basis bit") and a random bit for the key ("key bit") to create a qubit (e.g., using polarization or phase encoding) and sends this qubit to Bob.

The above mentioned publications by Bennet each describe a so-called “one-way” QKD system wherein Alice randomly encodes the polarization or phase of single photons at one end of the system, and Bob randomly measures the polarization or phase of the photons at the other end of the system. The one-way system described in the Bennett 1992 paper is based on two optical fiber Mach-Zehnder interferometers. Respective parts of the interferometric system are accessible by Alice and Bob so that each can control the phase of the interferometer. The interferometers need to be actively stabilized to within a portion of quantum signal wavelength during transmission to compensate for thermal drifts.

U.S. Patent No. 6,438,234 to Gisin (the ‘234 patent), which patent is incorporated herein by reference, discloses a so-called “two-way” QKD system that is autocompensated for polarization and thermal variations. Thus, the two-way QKD system of the ‘234 patent is less susceptible to environmental effects than a one-way system.

However, even in autocompensated QKD systems, only the optics layer is autocompensated. As it turns out, drifts can and do occur in the electronics necessary to stably operate the QKD system. For example, in a phase-encoding QKD system, if the voltage used to set the phase modulators drifts over time, then the phase imparted to the optical pulses will drift over time. The same is true for polarization modulators in polarization-encoding systems. This drift results in the pulses not having precise phase or polarization modulation, which reduces the ability to detect the encoded pulses.

Also, when performing the analysis of the basis measurements under the particular (e.g., the BB84 protocol), there needs to be a 50-50 chance of Bob’s detectors detecting signals measured in a basis different from Alice’s basis. To the extent this probability differs from 50-50, an eavesdropper has a potential advantage because the uncertainty associated with a “wrong” basis measurement is reduced.

Summary of the Invention

The present invention sets forth methods for autocompensating the modulators in a two-way QKD system. One aspect of the invention includes setting Bob's modulator voltage V_B to a positive value and then adjusting Alice's modulator voltage V_A in both the positive and negative direction to obtain overall phase modulations that show up in one or the other of two detectors. Bob's modulator voltage is then set to a negative value ($-V_B$) and the process repeated. When all of the basis voltages are set, the QKD system is operated with purposely selected incorrect bases at Bob and Alice to verify the appropriate probability of photon arrival at the detectors. If required, the modulator voltages are adjusted and the technique repeated until an appropriate detector count distribution is obtained for the incorrect measurement bases.

Brief Description of the Drawings

FIG. 1 is a schematic diagram of a two-way QKD system;

FIG. 2 is a flow diagram of an example embodiment of the method of performing modulator autocalibration as described in connection with the two-way QKD system of FIG. 1.

Detailed Description of the Invention

The present invention relates to quantum cryptography, and in particular relates to systems and methods for performing phase or polarization modulation in quantum key exchange (QKD) system. The ideal operation of a two-way QKD system is described immediately below, followed by descriptions of example embodiments of the timing set-up and modulator autocalibration methods that enable ideal or close-to-ideal operation of a QKD system on an ongoing basis.

Two-way QKD system

FIG. 1 is a schematic diagram of a two-way QKD system 100. Bob includes laser 12 that emits light pulses P0. Laser 12 is coupled to a time-multiplexing/demultiplexing (M/D) optical system 104. M/D optical system 104

receives input pulses P0 from laser 12 and splits each pulse into two time-multiplexed pulses P1 and P2. Likewise, optical system 104 receives from Alice (discussed below) pairs of time-multiplexed pulses and combines (interferes) them into a single pulse. Bob also includes a phase modulator MB coupled to an M/D optical system on the side opposite laser 12. Optical fiber link FL is coupled to phase modulator MB and connects Bob to Alice. Bob also includes a voltage controller 44 coupled to modulator MB, and a random number generator (RNG) unit 46 coupled to the voltage controller.

Bob also includes two detectors 32a and 32b coupled to M/D optical system 104, and a controller 50 operatively (e.g., electrically) coupled to laser 12, detectors 32a and 32b, voltage controller 44 and to RNG unit 46.

Alice includes a phase modulator MA coupled at one end to optical fiber link FL and at the opposite end to a Faraday mirror FM. Alice also includes voltage controller 14 coupled to modulator MA, and random number generator (RNG) unit 6 coupled to the voltage controller. Alice further includes controller 20 coupled to RNG unit 16 and to voltage controller 14.

Bob's controller 50 is coupled (optically or electronically) to Alice's controller 20 via synchronization channel SL to synchronize the operation of Alice and Bob. In particular, the operation of the phase modulators MA and MB is coordinated by controllers 20 and 50 exchanging synchronization signals SS. In an example embodiment, the operation of the entire system is controlled from either controller 20 or controller 50.

In the operation of QKD system 100, Bob's controller 20 sends a signal S0 to laser 12, which in response thereto initiates a relatively strong, short laser pulse P0, which is then attenuated by an optional variable optical attenuator VOA 13B. The (weak) pulse P0 arrives at M/D optical system 104, which splits the pulse into two weak pulses, P1 and P2, having orthogonal polarization. Pulse P1 goes directly towards Alice while P2 is delayed. Pulses P1 and P2 pass through MB (which remains inactivated at this point), and the pulses travel down the fiber to Alice.

Note that in another embodiment of system 100, pulses P0 and P1 can be relatively strong pulses that are attenuated by Alice using a VOA 13A located at Alice, wherein the pulses are attenuated to make them weak (quantum) pulses prior to them returning to Bob.

The pulses pass through Alice's modulator MA and reflect off of Faraday mirror FM, which changes the polarization of the pulses by 90°. As the pulses travel back through modulator MA, Alice lets the first pulse P1 pass therethrough unmodulated but modulates the phase (i.e., imparts a phase shift Φ_A to) second pulse P2. It should be noted here that Alice could also choose to modulate pulse P1 so that this pulse is twice-modulated. Since pulses P1 and P2 are later interfered, it is not the phase imparted to each pulse that matters, but rather the relative phase between the two pulses. The modulation of pulse P1 at Bob and pulse P2 at Alice is described for the sake of example.

The timing of the modulation is provided by the synchronization signal SS shared between controllers 20 and 50, as described in greater detail below. The modulation at Alice is carried out by controller 20 providing a well-timed signal S1 to RNG unit 16, which provides a signal S2 representative of a random number to voltage controller 14. In response, voltage controller 14 sends a voltage signal V_A (e.g., $V[+3\pi/4]$, $V[-3\pi/4]$, $V[+\pi/4]$, and $V[-\pi/4]$) to modulator MA to set the phase modulation to a corresponding value $+3\pi/4$, $-3\pi/4$, $\pi/4$ or $-\pi/4$.

The two pulses P1 and P2 then travel back to Bob, where pulse P2 passes unaltered through modulator MB, but imparts a phase shift Φ_B to pulse P1. The timing of the modulation of pulse P1 at Bob is provided by the synchronization signal SS shared between controllers 20 and 50, as described in greater detail below. The modulation is carried out by controller 50 providing a well-timed signal S3 to RNG unit 46, which provides a signal S4 representative of a random number to voltage controller 44. In response, voltage controller 44 sends a voltage signal V_B (e.g., $V[+\pi/4]$ or $V[-\pi/4]$) to modulator MB to set the phase modulation to a corresponding value $+\pi/4$ or $-\pi/4$.

Further, when pulses P1 and P2 enter M/D optical system 104, pulse P2 passes directly through but pulse P1 is delayed by an equal amount equal to that originally imparted to pulse P2. M/D optical system then interferes pulses P1 and P2.

The detectors 32a and 32b are arranged so that constructive interference ($\Phi_A - \Phi_B = 0$) is detected by detector 32a and destructive interference ($\Phi_A - \Phi_B = \pi$) is detected by detector 32b. When Bob imparts the same basis phase as Alice, a count in detector 32a indicates binary 0 and a count in detector 32b indicates binary 1. However, when Bob's basis phase is different from Alice's, there is no correlation and the count winds up in either detector 32a or 32b with equal probability (i.e., interfered the pulse has a 50:50 chance of being detected in either detector).

Modulator timing set-up

The description above relates to an idealized QKD system. However, in practice, such systems do not automatically operate in the ideal state. Further, a commercially realizable system must first be set up to operate and then must be able to compensate for changes in its operating state to ensure ongoing operation. The autocalibration methods set forth below presume that the modulator timing in QKD system 100 has been established.

Modulator autocalibration

As mentioned above, drifts can and do occur in the electronic layers of QKD systems during system operation. In a commercially viable QKD system, the drifts need to be automatically compensated so that the system can operate continuously. Accordingly, a method of performing modulator autocompensation is now described in connection with two-way QKD system 100.

With reference to FIG. 1 and to flow diagram 400 of FIG. 2, in 402 Bob provides a first select voltage —say $V[\pi/4]$ — to phase modulator MB corresponding to one of the basis phases. This voltage depends on the type of

modulator, but may be, for example, 1 volt. Voltage $V[\pi/4]$ sets modulator MB to a nominal phase setting of $\pi/4$.

Note that the voltages used to set the modulator to a select phase are each referred to below as a “basis voltage.”

In 404, in an example embodiment, Bob sends pulses P1 and P2 through modulator MB over to Alice, who modulates one of the pulses and then sends the pulses back to Bob, where they are detected as an interfered pulse in detector 32a or detector 32b. During this process, Alice’s voltage signal V_A for modulator MA is varied in the negative voltage range until the total phase shift imparted to the pulses is 0 (constructive interference). This is indicated by the pulses all being detected in detector 32a. This voltage is then set to be $V_A[-\pi/4]$.

It is worth noting that in 404, the pulses P1 and P2 returning to Bob from Alice are preferably weak (quantum pulses). However, these pulses could be strong pulses if used in combination with photodiode detectors arranged at Bob suitable for detecting strong pulses. For the sake of simplicity, however, quantum pulses are preferred, since the detectors in the system are single-photon detectors.

In 406, the voltage V_A provided to Alice’s modulator MA is again varied, but in the positive voltage range, until the total phase shift imparted to the pulses is π (destructive interference). This is indicated by the pulses all being detected in detector 32b. This voltage is then set to $V_A[+3\pi/4]$.

At this point, Bob’s voltage has been set at $V_B[\pi/4]$ and Alice’s corresponding voltages $V_A[-\pi/4]$ and $V_A[+3\pi/4]$ have been established.

In 408, Bob’s voltage is changed to the remaining voltage, which in this case is $V_B[-\pi/4]$. Acts 404 and 406 are then repeated to establish $V_A[\pi/4]$ by varying the positive voltage and to establish $V_A[-3\pi/4]$ by varying the negative voltage. Once this is accomplished, all of the (initial) voltages needed for modulating Bob’s modulator MB and Alice’s modulator MA are established.

In 410, pulses P0 are exchanged between Bob and Alice with fixed voltage settings that correspond to Bob making an “incorrect” basis measurement (i.e., the overall imparted phase to pulses P0 is not a multiple of π)

Bob's voltage is set to $V_B[\pi/4]$ and Alice is set at $V_A[\pi/4]$ so that Bob's modulator MB is set to $\pi/4$ and Alice's modulator is set to $+\pi/4$.

The distribution of counts in detectors 32a and 32b is then assessed, where detector 32a counts constructive interference and detector 32b counts destructive interference. Ideally, the count distribution should be equal since the probability of a count in each detector is 50:50 when Bob selects the incorrect phase basis.

In 412, if the number of counts in detector 32a is greater than that in detector 32b, then Bob's modulator voltage $V_B[\pi/4]$ is increased, and if it is less than that in detector 32b, then Bob's modulator voltage $V_B[\pi/4]$ is decreased. If the number of counts is found to be equal, then the method proceeds directly to 416.

In 414, acts 406 through 408 are repeated to re-adjust Alice's voltages $V_A[-\pi/4]$ and $V_A[3\pi/4]$ to correspond to Bob's new voltage as adjusted in 412.

In 416, acts 410 and 412 are repeated for Bob's remaining voltage, i.e., $V_B[-\pi/4]$. If Bob's remaining voltage needs to be adjusted to equalize the count number between the detectors, then in 418 acts 406 through 408 are repeated to adjust Alice's corresponding voltages $V_A[\pi/4]$ and $V_A[-3\pi/4]$.

Steps 410 and 416 are repeated until the ideal 50:50 detector count distribution is achieved,

Performing the above acts yields calibrated voltages for Bob's modulator MB and Alice's modulator MA. The QKD system is now ready for ideal operation. For security reasons, the above-described timing set-up and autocalibration procedures are preferably performed when Alice and Bob and optical fiber link FL are all in a secure location so there is no eavesdropper to alter the calibration. However, for the sake of necessity, the above-described procedures may need to be performed in the field even though this presents a security risk.

On-going modulator autocalibration

An example embodiment of the modulator autocalibration method of the present invention includes monitoring the counts in each detector that result from an incorrect basis measurement during the normal operation of the QKD system. As mentioned above, this count distribution should be 50:50 during system operation. After performing the QKD protocol, deviations from this count distribution can be used as a trigger to initiate the above-described autocalibration process so that it can be performed on an on-going basis.

In an example embodiment, the modulator timing set-up and autocalibration methods are accomplished by including software in controllers 20 and 40 that has instructions for carrying out the timing and autocalibration method discussed above and illustrated in the corresponding flow diagrams.

While the present invention has been described in connection with preferred embodiments, it will be understood that it is not so limited. On the contrary, it is intended to cover all alternatives, modifications and equivalents as may be included within the spirit and scope of the invention as defined in the appended claims.

MODULATOR AUTOCALIBRATION METHODS FOR QKD

ABSTRACT

Methods for autocompensating the modulators in a two-way QKD system are disclosed. The methods include setting Bob's modulator voltage to a positive value and then adjusting Alice's modulator voltage in both the positive and negative direction to obtain overall phase modulations that show up in one or the other of two detectors. Bob's modulator voltage is then set to a negative value and the process repeated. When all of the basis voltages are set, the QKD system is operated with purposely selected incorrect bases at Bob and Alice to assess whether the probability of photon detection is 50:50. If not, modulator voltages are adjusted and the technique repeated until a 50:50 detector count distribution is obtained for incorrect measurement bases.

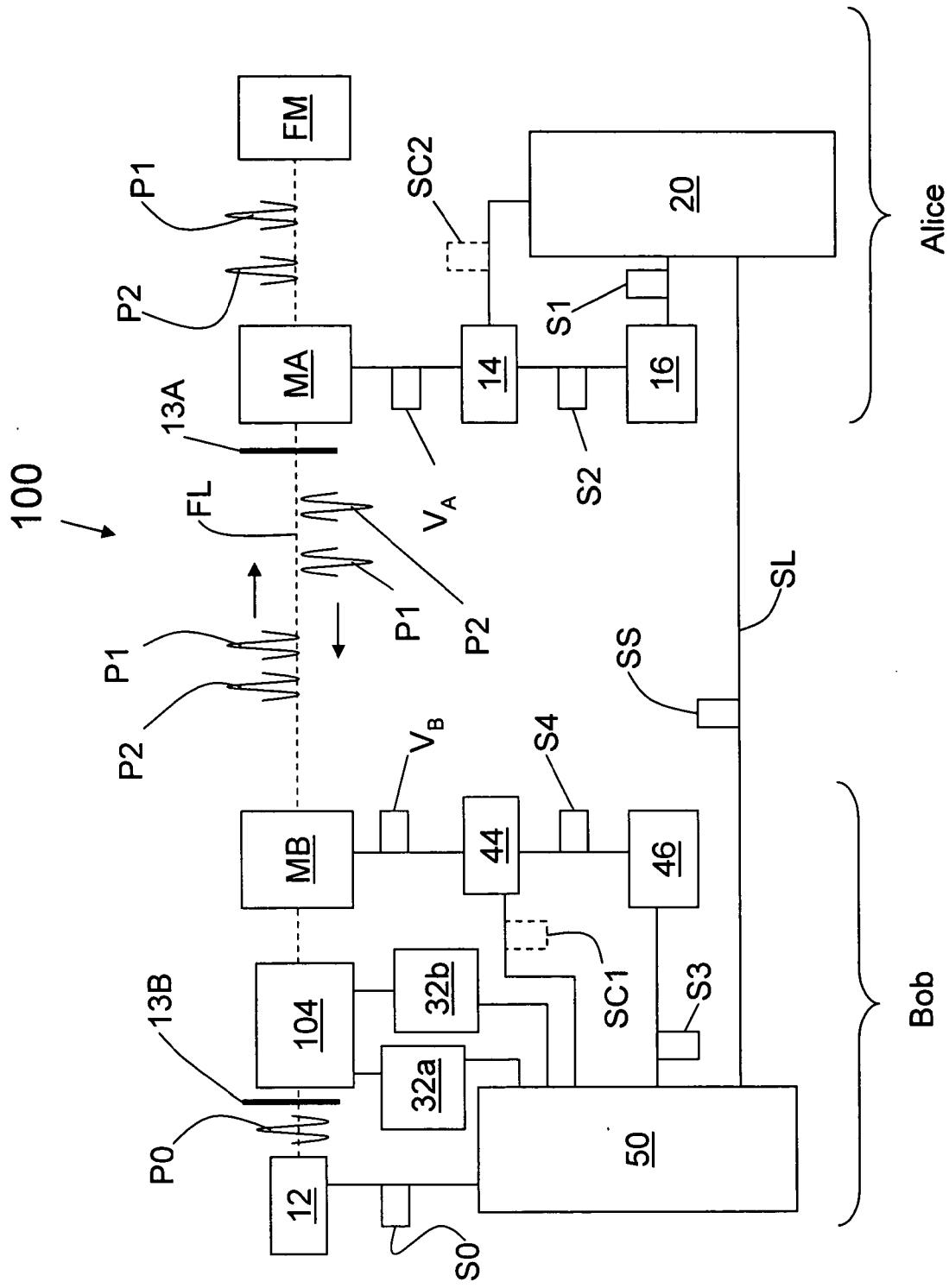


FIG. 1

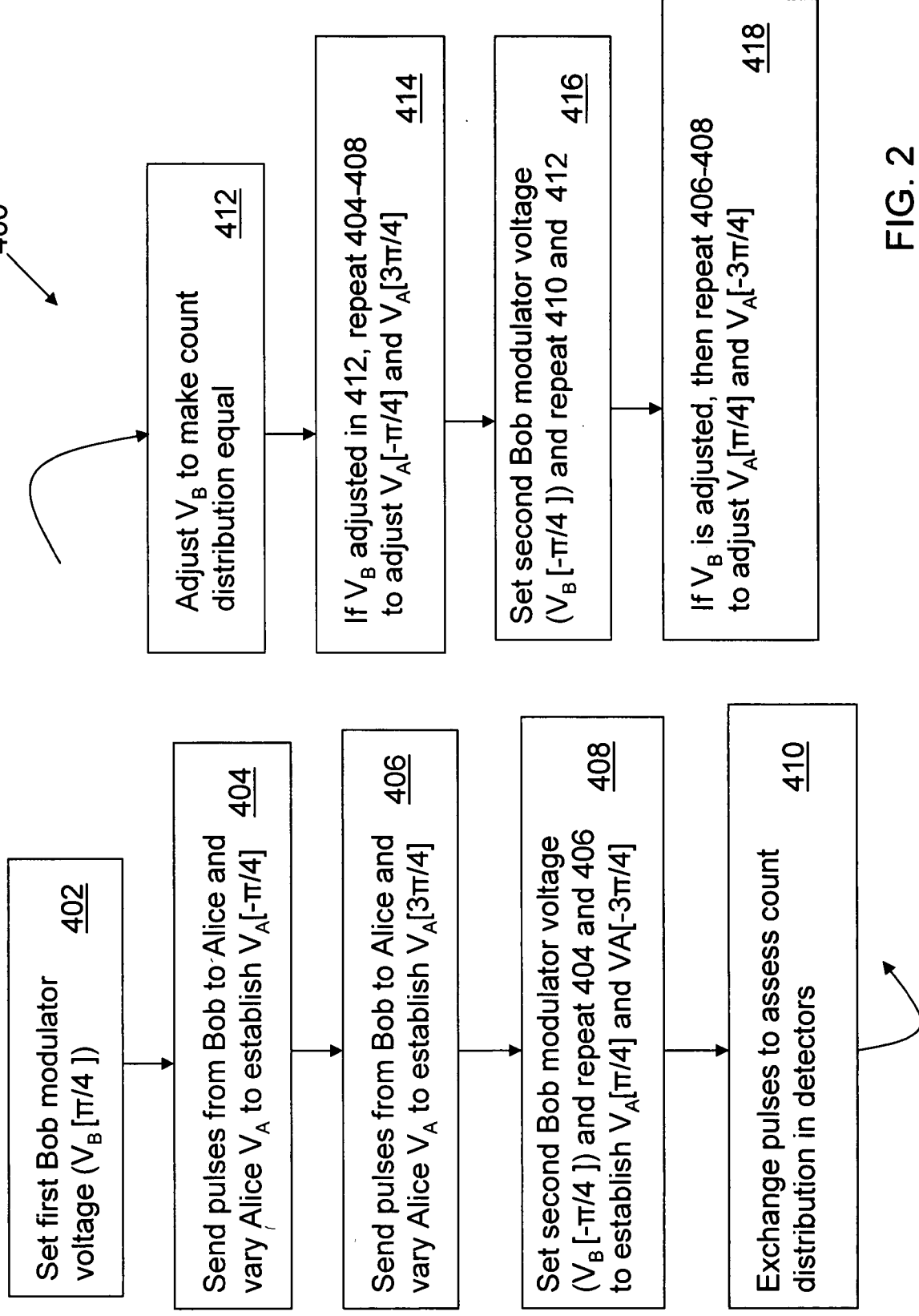


FIG. 2